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THE ION IMPACT ENERGY ON THE LHC VACUUM CHAMBER WALLS

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Abstract

The proton beam circulating in the LHC vacuum chamber will ionise the residual gas. The created ions are accelerated away from the beam and reach the vacuum chamber wall with some stored energy. The value of the ion impact energy is very important for the estimation of the ion stimulated gas desorption. The ion energy is studied as function of beam parameters. It is shown that the ion energy increases for a higher beam current and a smaller b-function. The ion energy is also sensitive to the bunch length and the bunch spacing. The ion energies are estimated for a number of different elements of the LHC. The effect of the magnetic field has been also studied

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THE ION IMPACT ENERGY ON THE LHC VACUUM CHAMBER WALLS

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Abstract

The proton beam circulating in the LHC vacuum chamber will ionise the residual gas. The created ions are accelerated away from the beam and reach the vacuum chamber wall with some stored energy. The value of the ion impact energy is very important for the estimation of the ion stimulated gas desorption. The ion energy is studied as function of beam parameters. It is shown that the ion energy increases for a higher beam current and a smaller β-function. The ion energy is also sensitive to the bunch length and the bunch spacing. The ion energies are estimated for a number of different elements of the LHC. The effect of the magnetic field has been also studied.

1 INTRODUCTION

Ions, created by ionisation of the residual gas by the proton beam, are repelled from the beam by its positive space charge depending on the beam parameters (bunch spacing and length), the beam size, the mass of ionised molecules and the position where the ions were created.

O.Gröbner has shown that the ion impact energy in the LHC can reach up to 7.2 keV for H_2^+ and 2.8 keV for CO^+ in the Interaction Region (IP), but it does not exceed 300 eV for H_2^+ and 200 eV for CO^+ in other places [1], [2]. W. Turner also made the estimation of the ion impact energy in the LHC. He obtained the following result: 13.1 keV for H_2^+ and 3.3 keV for CO^+ in the IP, 165 eV for H_2^+ and 134 eV for CO^+ in the arc [3]. These two estimations were made for the beam current I = 0.53 A in the arcs and I = 2×0.53 A at the IP. In both studies the effect of an external magnetic field was not taken into account.

The aim of this present study is to estimate the impact energy of ions bombarding the vacuum chamber walls of different elements of the LHC and to include the effect of magnetic fields at the relevant locations.

2 WITHOUT MAGNETIC FIELD

Following previous studies [1–3] we consider a circular beam with a Gaussian profile. The time-averaged electric field of the beam can be given in SI units by:

$$E = \frac{I}{2\pi\varepsilon_0 c}\frac{1-e^{-(r/\sigma_r)^2}}{r}; \qquad (1)$$

where I is the proton beam current; $\varepsilon_0 = 8.85\cdot10^{-12}$ [F/m] is the permitivity of free space; c is the speed of light in vacuum; σ_r is the rms beam size, $\sigma = \sqrt{\beta\varepsilon_n/\gamma}$, where for LHC: $\varepsilon_n = 3.75\cdot10^{-6}$ m·rad, $\gamma = 7460.6$; r is the distance from the centre of beam to the ion.

In the estimation with a continuous (unbunched) beam the ions arrive at the vacuum chamber wall with a kinetic energy equal to the difference in potential between the point of the ionisation and the wall:

$$W(r_0) = \int_a^R E(r)\,dr; \qquad (2)$$

where a is the radial position where the molecule was ionised and R is the internal radius of the vacuum chamber. The probability of ionisation $\rho(a)$ of the residual gas molecules is proportional to a Gaussian distribution and the initial radial position a:

$$\rho(a) \propto 2\pi r e^{-(a/\sigma_r)^2}; \qquad (3)$$

then the numerical integration of equation (2) with K different initial radial positions, a_k (for example: $a_k=3\sigma_r/k$, $k = 1,2,\ldots K$), gives the average value of ion energies:

$$<W>= \sum_{k=1}^{K} w_k W(r_k); \qquad (4)$$

where w_k is the weight of $W(a_k)$:

$$w_k = \rho(a_k) \Big/ \sum_{j=1}^{N} \rho(a_j).$$

The estimation described above does not take into account the effect of a bunched beam. In the LHC, the bunch length is $\tau = 0.257$ ns and the bunch spacing is $T = 24.95$ ns. Hence, the peak of the electric field, E_b, is about 100 times higher.

$$E_b = \frac{I}{2\pi\varepsilon_0 c}\frac{1-e^{-(r/\sigma_r)^2}}{r}\frac{T}{\tau}. \qquad (5)$$

A newly created ion is accelerated by the peak electric field during the bunch passage and then drifts with a constant velocity until the next bunch arrives. An estimation of its final velocity can be obtained by numerical integration. The iteration formulae for ion velocity and the radial position in the presence of a bunch are:

$$\begin{cases} v_n = v_{n-1} + E_b \dfrac{q}{m}\cdot\Delta t; \\ r_n = r_{n-1} + v_n\cdot\Delta t; \end{cases} \qquad (6)$$

where $\Delta t = \tau / N$ is the time interval, $n = 1,2\ldots N$. The time interval should be chosen small enough so as not to influence the final result. This requirement was found to be satisfactory for $N = 1000$. Between two bunches the ion drifts with velocity $v_d = v_N$ to the radial position r_d when a new bunch arrives: $r_d = r_N + v_N(T-\tau)$.

Since the ion can be created at a different radial position and anywhere along the length of the bunch, the duration of acceleration of the ion by the first bunch, τ_1, is $0<\tau_1\leq\tau$. For $\tau_1 = \tau\, m / M$ (m = 1,2…M) the formula for the average ion impact energy is:

$$<W> = \frac{1}{M}\sum_{m=1}^{M}\sum_{k=1}^{K} w_k W_k\left(a_k, \frac{m}{M}\tau\right). \qquad (7)$$

The results of such estimations depend on the variation of the beam β-function, the beam current and weakly on the vacuum chamber dimensions. The bunching effect is significant for the beam with β<100 m (see Fig. 1), in the LHC this is around the IR only. In another places with higher values of β, taking into account the bunching effect gives less than 10% higher value then the estimation for a continuous beam.

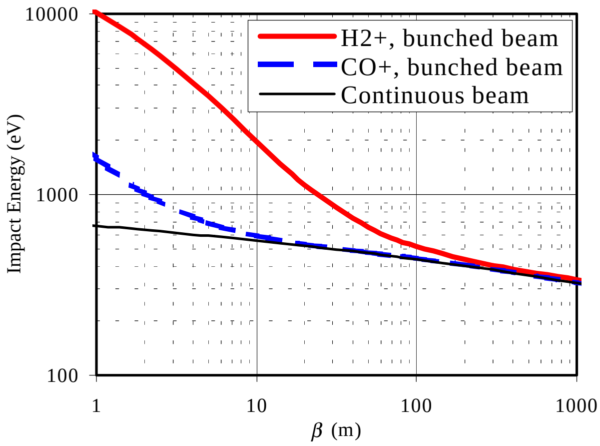


Figure 1. The ion impact for a beam current I=2×0.85A in a 50-mm vacuum chamber.

It was found that the ion energy increases approximately linearly with the beam current between 0.1 A and 1.7 A. The ion energy is not uniform along the vacuum chamber containing both beams; it depends on whether or not the beams arrive at a given location in phase or with a time delay. The highest average ion impact energy is reached in the places where the beams arrive simultaneously, the lowest one is about 2 times lower where the beams arrive in anti-phase. The values of estimated average energy of ions for some elements of the LHC are presented in Table 1.

3 IN A MAGNETIC FIELD

Along most of the circumference of the LHC the vacuum chambers are inside magnetic elements: dipoles, quadrupoles, or solenoids. The magnetic field will bend the trajectory of the created ions, accelerated by the electric field, and its impact energy can then differ from the estimation made in Section 2 above.

The iteration formulas for the ion velocity and the radial position in a magnetic field **B** = (B_x, B_y, B_z) are

$$\begin{cases} \mathbf{v}_n = \mathbf{v}_{n-1} + \frac{q}{m}\left(\mathbf{E} + \mathbf{v}_{n-1}\times\mathbf{B}\right)\cdot\Delta t; \\ \mathbf{r}_n = \mathbf{r}_{n-1} + \mathbf{v}_n\cdot\Delta t; \end{cases} \qquad (8)$$

where **E**=($E_b\cos\alpha$, $E_b\cos\alpha$, 0) during the bunch passage otherwise **E** = 0. The axes X, Y and Z correspond to the horizontal, vertical and longitudinal axis.

Table 1. The average ion impact energy in solenoid (S), quadrupole (Q), dipole (D) and no (–) magnetic field.

Location and field		Impact energy (keV)			
		At I_b=0.85A		at I_b=0.56A	
		H_2^+	CO^+	H_2^+	CO^+
IP1	–	13.6	2.7	7.5	1.3
IP1	S	20–75	2.7–8	20–70	2.7–8
IP5	S	80–300	6–23	80–300	6–23
Q1–Q7	–	0.15–0.30	0.145–0.29	0.095–0.20	0.094–0.19
	Q	0.20–0.50		0.13–0.34	
D1	–	0.15–0.30	0.15–0.30	0.10–0.20	0.10–0.20
	D	0.16–0.33		0.11–0.22	
D2–D4	–	0.184	0.180	0.120	0.119
	D	0.200		0.130	
Arc	–	0.240	0.225	0.152	0.148
	D	0.270		0.175	
	Q	0.390		0.220	

3.1 *Dipole magnetic field*

The dipole magnetic field strength in the arc is nominally B = 8.4 T. The magnetic field strength in the separation dipoles D1–D4 are B = 1.4 T or B = 3.5 T.

The result of estimations are that the H_2^+ impact energy is higher by factor of 1.05 to 1.15 in the presence of the dipole magnetic field while CO^+ impact energy does not change. The ions spiral in the dipole field and bombard two strips (top and bottom) along a dipole vacuum chamber. The width of these strips is ~2 mm in an arc dipole and ~4 mm in the separation dipoles D1–D4. The incident angle varies between normal and very grazing angles.

3.2 *Quadrupole magnetic field*

The quadrupole magnetic field can be described as: **B** = ($Gr\sin\alpha$, $Gr\cos\alpha$, 0), where G is the gradient of the quadrupole magnetic field, α is the angle of radius-vector **r** = ($r\cos\alpha$, $r\sin\alpha$, 0).

The estimations of the ion impact energy in the quadrupoles were made for the maximum gradient of the quadrupole magnetic field G = 240 T/m. The H_2^+ impact energy increases by 1.3 to 1.7 times in the presence of the quadrupole magnetic field while CO^+ has practically the same impact energy in both cases. The results of estimations of ion impact energies are presented in Table 1. Estimations show that the ion migration along the vacuum chamber does not exceed the diameter of the vacuum chamber. The ions will bombard four ~4-mm strips along a vacuum chamber in a quadrupole (see Fig. 2), i.e. about 10% of vacuum chamber surface.

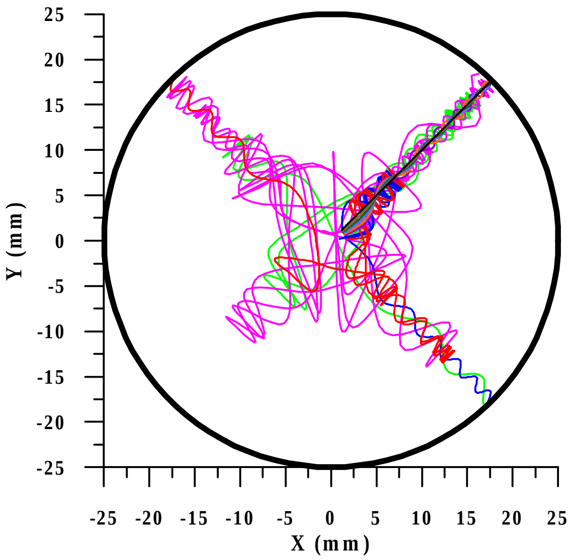
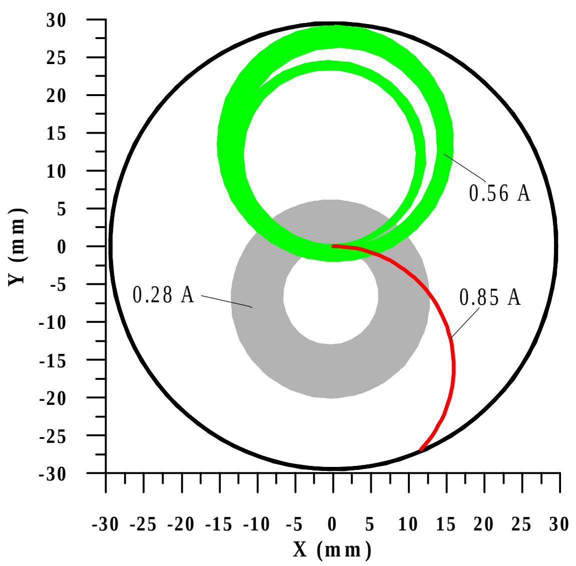


Figure 2. The H_2^+ trajectories in the quadrupoles.

3.3 *Solenoid magnetic field*

A solenoid field is used in the inner detectors of ATLAS (B=2 T) at IP1 and CMS (B=4 T) at IP5. The estimation of the ion energy in a solenoid field $\mathbf{B} = (0, 0, B)$ was made for a vacuum chamber with diameter of 58 mm for $\beta = 0.5$ m (IP), $\beta = 2.5$ m and $\beta = 10$ m. It was shown that the ions reach the vacuum chamber wall after between one and a few hundred bunches. The larger the current the fewer bunches are necessary for the ion to reach a wall. The range of ion impact energies are shown in Table 1. The longitudinal drift of the ions having an initial energy of about 1 eV after 1000 bunch passages is estimated to be less then 0.25 m, i.e. the ions remain practically with the same co-ordinate Z.

Figure 3. The H_2^+ trajectories in the solenoid field.



Since the trajectories of the ions are bent in the solenoid magnetic field they may reach the vacuum chamber wall only if the bending radius is larger then the half radius of the vacuum chamber otherwise the ion will return to the beam. This gives the minimal necessary energy of ions reaching the wall of vacuum chamber with radius R in a solenoid magnetic field. The upper energy limit can be also estimated: the bending radius of an ion is less then the radius of the vacuum chamber. The results of the estimation with the iteration formula (8) lie in the energy range estimated from the bending radius. The results are presented in Table 1. It may be important to note that the ions bombard the wall at grazing incident angles, which can increase the desorption yield.

4 CONCLUSIONS

1. The estimation of the ion impact energy in the LHC vacuum chamber without magnetic field shows the following:

- The ion impact energy depends mostly on the beam current and the β-function. There is a very weak dependence on a vacuum chamber radius in the range ID = 40 mm to ID = 100 mm.
- The average energy of an ion at maximum beam current (2×0.85 A) is 13.6 keV for H_2^+ and 2.7 keV for CO^+ at the IP. In other places it does not exceed the value of 300 eV for H_2^+ and CO^+. The ions bombard the wall at normal incidence.

2. In presence of the dipole magnetic field, the H_2^+ ion energy increases by about 1.1 times, the energy for CO^+ ions is insensitive to the dipole magnetic field. The average energy of ions in the dipoles does not exceed the value of 270 eV for H_2 and 225 eV for CO^+. The ions bombard a wall at different incident angles.

3. In presence of the quadrupole magnetic field, the H_2^+ ion energy increases by 1.3 to 1.7 times, while the energy for CO^+ ions is rather insensitive to the quadrupole magnetic field. The average energy of ions in the quadrupoles does not exceed the value of 500 eV for H_2 and 300 eV for CO^+. The ions bombard a wall at different incident angles.

4. In presence of the solenoid magnetic field ion impact energy near IP depends on the vacuum chamber dimensions and the magnetic field but does not depend on the β-function:

- The ion impact energy in ATLAS lies in range 20 to 75 keV for H_2^+ and 2.7 keV to 8 keV for CO^+.
- The ion impact energy in CMS lies in range 80 keV to 300 keV for H_2^+ and 5.8 keV to 8 keV for CO^+.
- The ions bombard a wall at very grazing incident angles.

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